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ABSTRACT

This study was prompted by the special interest in sugar crops, at a time of high petroleum prices and fuel shortages, as potential renewable resources which would supplement non-renewable fossil resources. Four to six sweet sorghum [*Sorghum bicolor* (L.) Moench] cultivars were evaluated 4 yr for fermentable sugar production potential at eight locations in the continental USA and at one location in Hawaii. Latitudes represented ranged from 21 to 47°N with the average number of frost-free days ranging from 120 to more than 350. Data were collected for biomass yield, percent lignin, percent cellulose, stalk sugar yields, and other agronomic characters. Total sugar yield for the continental USA ranged from 4 Mg ha^{-1} to 10.7 Mg ha^{-1} during 3 yr of the study and up to 12 Mg ha^{-1} at the Hawaiian location. Accordingly, theoretical ethanol production in the continental USA ranged from 2129 L ha^{-1} to 5696 L ha^{-1}. Results of the study demonstrated that sweet sorghum is far more widely adapted than was anticipated for a plant of tropical origin and certainly has the potential for providing a good source of fermentable carbohydrates across a wide geographic area.

Additional index words: Ethanol, Biomass, Lignin, Cellulose, Sucrose, Glucose, Fructose, *Sorghum bicolor* (L.) Moench.

ETHANOL (EtOH) production in the USA was expected to grow to about 3125 million liters in 1986 from an estimated 2841 million liters in 1985 (11). This growth in EtOH production is principally the result of increased demand for an octane enhancer in regular and unleaded gasoline. The EPA upper limits for lead content in gasoline have been reduced to 26 mg L^{-1} effective 1 Jan. 1986, and complete elimination of lead from gasoline has been proposed for 1988.

Although EtOH can be manufactured from a large number of commodities, the chief product used in the USA is maize (*Zea mays* L.). In Brazil, the world's largest EtOH producer, sugar from sugarcane (*Saccharum* spp.) is used to produce EtOH.

Sugar crops are of special interest in EtOH production because these renewable resources achieve high yields, grow in many countries, and can be converted into EtOH by application of relatively simple technology. In addition, EtOH production from sugar crops would provide an alternative market for low-cost agricultural commodities.

Sweet sorghum [*Sorghum bicolor* (L.) Moench] is a coarse grass herbaceous annual that in the tropics can be ratooned to produce successive crops. Sweet sorghum is currently grown for syrup, forage, and sil-

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age (6). Sweet sorghum resembles sugarcane in that the stalk (culm) storage organ contains appreciable sugar and enough fiber to generate process steam. However, sweet sorghum differs markedly from sugarcane in that it is planted from seed and can be grown to maturity in 90 to 180 days. The short growing season capability should allow this tropically adapted plant to be grown in geographical areas with a temperate climate during their warm season.

Although sweet sorghum has been grown on relatively small land holdings for more than 100 yr, its development as a crop plant is far behind maize, sugarbeet, or sugarcane. However, since sweet sorghum is planted from seed and is grown as a row crop, its culture resembles maize or other seed-planted row crops. Planting methods used for other row crops can be adapted to sweet sorghum. Breeding efforts with sweet sorghum certainly could be expected to produce significant improvement in fermentable sugar yield.

This research was designed to determine the adaptability and yield potential (especially potential EtOH production) of sweet sorghum at widely diverse geographic locations. The geographic test sites selected, for the most part, are not normally associated with sweet sorghum production.

MATERIALS AND METHODS

Field experiments were conducted in 1980 through 1983 at six to eight geographic locations ranging from 21 to 47° N latitude (Table 1). Four or six sweet sorghum cultivars (depending on seed supplies) were grown at each location in each of the 4 yr of the study. Having little information on their potential for sugar production, the selection of cultivars was based on diversity of origin. Cultivars grown included, 'Dale', 'Keller', 'Rio', 'Wray', 'M 81E' and 'MN 1500'. The last cultivar is of known African origin, while the other cultivars are products of USA breeding programs. The cultivars were grown in a randomized complete block design with four replications. Plots consisted of three 7.6-m rows spaced 0.8 m apart. Data were obtained from plants harvested from the middle 6.4 m in the center row of each plot. Care was taken to reduce border effects due to unequal competition of cultivars by the appropriate use of sorghum buffer rows. Fertilizer and irrigation applications were the standard practices for growing maize at each location.

Prior to harvest, average heading date was determined. A cultivar was considered headed when 50% of the plants had panicles out of the boot. At harvest, the center row of each plot was cut at ground level and weighed (gross green weight). Gross green weight consisted of leaves, stalks, and panicles when present. Panicles were included as part of stalk weight because, with the exception of California and Hawaii, seed produced in the panicles was negligible. Plant height was measured, and leaves were then stripped from the stalks and weighed separately. Stalk diameter and brix were both determined from a 10-stalk sample from each plot. Brix determinations were made with a hand refractometer by reading a composite juice sample obtained from the midpoint of stalks. Dry weight of leaves and stalks were determined from each 10-stalk sample. Samples of leaves and chopped stalks were weighed green and re-weighed after oven drying at 60°C for 30 h.

Stalk samples from each plot were frozen immediately and later packed in dry ice for shipment to the Northern Agricultural Energy Center (NAEC) in Peoria, IL for analyses of sugar, cellulose, and lignin. Lignin and cellulose were determined in 1980 and 1981 and glucose, sucrose, and fructose in 1980, 1981, and 1982. Sucrose, glucose, and fructose were determined by HPLC analyses. Frozen stalk samples received at NAEC were split lengthwise and then freeze-dried in a Vir Tis sublimator (Model 100-SRC).[3] These dried sections, containing about 10 g water kg^{-1} were ground in a Thomas-Wiley mill (Model ED-5) with a sieve containing 1-mm diam. perforations. A 2.0-g sample (dry solids basis) in 25 mL of 500 mL L^{-1} aqueous ethanol (v/v) was shaken 2 h at room temperature. The mixture was then centrifuged 10 min at 10 000 rpm. The supernatant was subsequently analyzed for sugar (sucrose, glucose, and fructose) content by HPLC using a Bio Rad HPX-42 size exclusion column with water as the mobile phase. This analysis was known to remove all stalk sugars and thus result in extracts with essentially only sucrose, glucose, and fructose. Total sugars were determined by addition of these separate sugars. Since individual sugars were not determined in 1983, total sugar in 1983 was estimated using net stalk weight and brix. Stalk sections also were analyzed for cellulose and lignin as follows. The ground freeze-dried materials (6 to 7 g, dry solids basis) were extracted 24 h with 800 mL L^{-1} (80%) aqueous ethanol (v/v) in a Soxhlet apparatus to provide sugar-free meals for lignin and alkali solubility determinations. The meals were removed from the Soxhlet thimble, spread out in a shallow tray, and air-dried (2,5). Lignin contents were determined by a spectrophotometric method (2) and solubilities in 0.25 *M* sodium hydroxide were determined by TAPPI standard T4m-59 (10). Total cellulose content was estimated by the difference between the total plant material and the combined lignin, sugars, and alkali-soluble contents. Data are reported on a moisture-free basis determined by drying representative material, at 105°C, to constant weight.

Alcohol yields are theoretically directly proportional to the starch or sugar content of the feedstock. The theoretical yield of ethanol (EtOH) is 568 g kg^{-1} starch, 510 g kg^{-1} of glucose or fructose, and 537 g kg^{-1} sucrose. Ethanol weighs 789.3 g L^{-1}; therefore 5.83 kg of glucose or fructose or 5.54 kg of sucrose are required to make 3.78 L of EtOH. For purposes of this study, the average of the glucose and sucrose values (5.68 kg) was used in EtOH yield calculations. Theoretical EtOH yields were calculated by dividing total sugar yield (Mg ha^{-1}) by 5.68 kg, which is equivalent to 12.51 lbs of sugar per gallon of EtOH. The resulting values were then converted to liters by multiplying by 3.78. Yields of EtOH generally fall short of theoretical yields because about 50 g kg^{-1} (5%) of the sugar is used by the yeast to produce new cells and minor products such as glycerols, acetic acid, lactic

[3] Mention of a trademark or proprietary product does not constitute a guarantee or warranty for the product by the USDA-ARS and does not imply approval to the exclusion of other products that might also be suitable.

Table 1. Locations, degrees North latitude, and years of tests to evaluate biomass and ethanol production potential of sweet sorghum.

Location	Degrees N latitude	Test years	Average no. frost-free days
Fargo, ND	47	1982, 1983	120
East Lansing, MI	43	1980–1983	140
Logan or Farmington, UT	41.8	1980–1983	140
Fort Collins, CO	40.8	1980–1983	143
Beltsville, MD	39	1980–1983	180
Davis, CA	38.5	1980–1982	280
Brawley, CA	33	1980–1983	300
Meridian, MS	32	1980	240
Aiea or Kunia, HI	21	1981, 1983	350

acid, and fusel oils (3). Because of this and other losses associated with extraction of sugar from feedstock, we project 80% of theoretical EtOH yield as a more practical figure for large scale processing. Accordingly, EtOH values discussed in the text and presented in the tables have been multiplied by 0.8.

RESULTS

Data for certain agronomic traits and biomass, sugar, and theoretical ethanol yields are summarized by year in Tables 2 through 5. Ranges and across year averages for theoretical ethanol yield and factors directly affecting EtOH production are presented in Table 6.

Agronomic Traits

Plant height across the 4 yr of the study averaged 2.79 m with a range of 2.61 m in 1980 to 3.15 m in 1983. As anticipated, plant height was greatest (3.88 m) at the Aiea, HI location (23° N latitude) and least at the most northerly location (Fargo, ND, 47° N), averaging 2.17 m. In the continental USA, plants were consistently tallest at the Davis, CA location with a 4-yr average of 3.32 m. Significant lodging was seen in nearly all cases where plant height exceeded about 3.00 m. In the two cases where plant height was below 2.00 m, adverse weather conditions delayed planting, thus reducing the effective growing season (Tables 2 and 4). Stalk diameter was a very consistent trait across years and locations averaging 15 mm with a range of 12 to 19 mm (Tables 2 to 5).

Days to heading (tabular data not presented) varied within and across locations as expected. Variation within locations was due to cultivar differences. The Hawaii test site produced the shortest days to heading for all cultivars with a range of 61 to 79 days. In the continental USA, at the North Dakota and Michigan test sites, four of the six cultivars headed in 88 to 98 days. Two cultivars, MN 1500 and M 81E, did not head in North Dakota but did in Michigan after 119 days. At the Colorado and Utah locations, four of six cultivars headed in 103 to 139 days. At both of these locations and at the two California locations, the cul-

Table 2. Agronomic traits and biomass, sugar, and theoretical ethanol (EtOH) yields of four sweet sorghum cultivars grown at seven geographic locations in 1980.

Location	Plant height	Stalk diam.	Gross green wt.	Net stalk wt.	Dry matter	Lignin	Cellulose	Glucose	Fructose	Sucrose	Brix	Total sugars	EtOH†
	m	mm	Mg ha^{-1}		g kg^{-1}			Mg ha^{-1}			degrees	Mg ha^{-1}	L ha^{-1}
East Lansing, MI	3.16±0.14‡	12±1	89.3± 9.8	57.2±10.7	236±28	16±3	47±10	0.3±0.7	0.7±0.8	3.9±1.4	16.4±0.6	4.9±1.1	2608± 568
Logan, UT	1.67±0.43	18±2	67.4± 7.5	54.6± 6.2	243±28	14±3	61± 8	1.2±0.5	1.6±0.5	1.4±1.1	4.8±1.8	4.3±0.7	2289± 373
Fort Collins, CO	2.28±0.29	16±1	93.3±10.6	65.2± 8.7	243±28	14±2	56± 6	1.5±0.9	0.6±0.6	2.9±1.4	10.8±2.9	5.1±0.8	2715± 442
Beltsville, MD	2.50±0.17	15±1	55.3± 5.6	46.0± 4.8	243±28	13±4	42±10	0.2±0.6	0.2±0.5	4.2±1.0	19.4±1.6	4.5±1.0	2395± 502
Davis, CA	3.22±0.27	--	126.7±28.0	91.5±21.0	243±28	14±2	49± 7	1.7±0.9	1.7±1.0	7.3±3.0	--	10.7±2.8	5696±1463
Brawley, CA	2.21±0.26	18±4	79.3±15.1	60.1±10.8	250±28	13±4	42±11	--	--	6.4±1.5	20.7±2.3	6.4±1.5	3407± 780
Meridian, MS	3.25±0.12	17±2	57.4± 5.1	43.2± 4.7	236±28	15±4	48±11	0.5±0.3	0.3±0.2	4.2±0.6	17.7±1.7	4.9±0.5	2608± 284

† To convert liters per hectare (L ha^{-1}) to gallons per acre, divide by 9.35. ‡ ± denotes SE.

Table 3. Agronomic traits and biomass, sugar, and theoretical ethanol (EtOH) yields of four sweet sorghum cultivars grown at seven geographic locations in 1981.

Location	Plant height	Stalk diam.	Gross green wt.	Net stalk wt.	Dry matter	Lignin	Cellulose	Glucose	Fructose	Sucrose	Brix	Total sugars	EtOH†
	m	mm	Mg ha^{-1}		g kg^{-1}			Mg ha^{-1}			degrees	Mg ha^{-1}	L ha^{-1}
East Lansing, MI	2.41±0.29‡	13±1	76.2±10.2	53.8±11.0	240±22	14±3	54± 7	0.6±0.8	0.6±0.5	2.8±1.7	16.4±1.8	4.0±1.4	2129± 764
Logan, UT	3.05±0.22	15±1	69.8±11.4	55.7±10.0	240±22	14±3	55± 8	0.9±0.5	0.6±0.4	2.6±1.1	13.8±2.2	4.1±0.8	2182± 436
Fort Collins, CO	3.26±0.22	19±1	98.5± 9.8	76.3±10.0	240±22	16±2	65± 6	1.8±1.1	1.4±1.0	3.1±2.3	12.9±2.7	6.3±1.4	3354± 758
Beltsville, MD	3.63±0.17	16±1	78.8±11.1	67.8± 9.4	240±22	14±3	52± 9	0.6±0.7	0.4±0.6	4.6±1.4	17.6±2.5	5.6±1.1	2981± 596
Davis, CA	3.50±0.33	18±2	118.1±21.3	97.3±18.9	240±22	16±3	61±12	1.0±0.9	1.0±0.5	3.1±2.0	--	5.1±2.0	2715±1031
Brawley, CA	2.85±0.30	14±2	76.2±11.2	58.9± 8.6	240±22	13±2	53± 9	0.7±0.6	0.4±0.3	4.2±1.1	17.0±1.9	5.3±0.8	2821± 411
Aiea, HI	3.23±0.31	16±2	121.9±31.0	95.2±24.2	--	--	--	--	--	12.0±3.5	17.2±1.9	12.0±3.5	6388±1597

† To convert liters per hectare (L ha^{-1}) to gallons per acre, divide by 9.35. ‡ ± denotes SE.

Table 4. Agronomic traits and biomass, sugar, and theoretical ethanol (EtOH) yields of four sweet sorghum cultivars grown at seven geographic locations in 1982.

Location	Plant height	Stem diam.	Gross green wt.	Net stalk wt.	Dry matter	Glucose	Fructose	Sucrose	Brix	Total sugars	EtOH†
	m	mm	Mg ha^{-1}		g kg^{-1}	Mg ha^{-1}			degrees	Mg ha^{-1}	L ha^{-1}
Fargo, ND	1.74±0.26‡	16±1	55.3± 9.6	45.3± 8.1	241±22	1.1±0.3	0.8±0.3	2.2±1.2	12.6±1.9	4.1±0.8	2182± 425
East Lansing, MI	2.69±0.28	14±1	99.6±16.9	76.1±15.4	241±22	1.5±0.8	1.0±0.7	5.2±1.5	15.2±1.8	7.8±1.5	4152± 809
Logan, UT	--	14±2	63.5±19.6	53.9±17.5	241±22	1.4±0.6	1.1±0.5	2.6±1.5	13.2±2.2	5.1±2.0	2715±1066
Fort Collins, CO	2.72±0.29	19±2	81.0±14.3	66.2±12.1	230±26	1.6±0.8	1.2±0.7	3.4±1.8	12.0±3.0	6.2±1.8	3300± 970
Beltsville, MD	3.31±0.22	15±2	74.1±11.8	63.0± 9.8	241±22	1.1±0.5	0.7±0.4	4.8±1.4	16.8±2.3	6.7±1.1	3567± 602
Davis, CA	3.29±0.28	19±3	100.7±21.2	83.0±19.0	241±22	1.7±0.7	1.3±0.7	4.1±2.0	--	7.1±1.9	3780± 986
Brawley, CA	2.53±0.17	14±1	85.8±11.3	71.0± 8.6	230±26	1.4±1.0	0.5±0.8	4.8±1.4	17.0±3.2	6.7±1.1	3567± 570

† To convert liters per hectare (L ha^{-1}) to gallons per acre, divide by 9.35. ‡ ± denotes SE.

tivar Wray was consistently late heading (130 to 164 days). Also, at the Colorado, Utah, and Brawley, CA location, the cultivar M 81E required more than 130 days to head.

Biomass Yield Factors

Average gross green weight (fresh weight) ranged from 66 Mg ha^{-1} at Meridian, MS, to 115 Mg ha^{-1} at Davis, CA. Percentage harvest weight attributable to stalks averaged 790 g kg^{-1} (79%) across locations and years with a range of 700 g kg^{-1} (70%) at the Michigan location to 850 g kg^{-1} (85%) at the Maryland test site. Average net stalk weight ranged from 52 Mg ha^{-1} to 91 Mg ha^{-1}. At specific location-year combinations, net stalk yields of more than 100 Mg ha^{-1} were observed (Table 6).

Dry matter percentage, determined from stalk samples, averaged a consistent 240 g kg^{-1} (24%) for the first 3 yr of the study. In the last year of the study (1983), somewhat less uniformity among locations was observed (Table 5).

Lignin and cellulose values determined from stalk samples in 1980 and 1981 are presented in Tables 2 and 3, respectively. Both of these characters were relatively consistent across the locations and the 2 yr. Lignin averaged 14 g kg^{-1} (1.4%) (range 13 to 16 g), and cellulose averaged 52 g kg^{-1} (5.2%) (range 42 to 65 g).

Sugars

Sucrose was the predominant stalk sugar but significant amounts of glucose and fructose contributed to total sugar yield (Tables 2 through 4). Discernable trends across the test locations and years were not apparent for glucose or fructose and amounts were relatively small compared to sucrose. Glucose yield ranged from a low of 0.2 Mg ha^{-1} at Beltsville, MD in 1980 to 1.8 Mg ha^{-1} at Fort Collins, CO in 1981. Fructose ranged from 0.2 Mg ha^{-1} at Beltsville in 1980 to 1.7 Mg ha^{-1} at Davis, CA also in 1980.

Sucrose yield in the continental USA for 1980 through 1982 ranged from 1.4 Mg ha^{-1} at Logan, UT in 1980 to 7.3 Mg ha^{-1} at Davis, CA in 1980. As expected, the Hawaiian test site had the highest sucrose yield (12 Mg ha^{-1}). In the continental USA, average sucrose yields were frequently greater than 4 Mg ha^{-1} from 1980 through 1982 (Tables 2 through 4). Hand refractometer brix taken at stalk midlength was not highly correlated with any of the individual sugars or with total sugar.

Theoretical Ethanol Yield

Theoretical EtOH production, which is based on total sugar yield, ranged from a low of 2129 L ha^{-1} at the Michigan test site in 1981 to 6388 L ha^{-1} at Aiea, HI in 1981. Theoretical EtOH yield varied considerably among years at several of the test locations (Ta-

Table 5. Agronomic traits and biomass, sugar, and theoretical ethanol (EtOH) yields of four sweet sorghum cultivars grown at seven geographic locations in 1983.

Location	Plant height	Stem diam.	Gross green wt.	Net stalk wt.	Dry matter	Brix	Total sugars	EtOH†
	m	mm	Mg ha^{-1}		g kg^{-1}	degrees	Mg ha^{-1}	L ha^{-1}
Fargo, ND	2.61 ± 0.23‡	18 ± 2	90.6 ± 10.4	74.9 ± 8.0	170 ± 25	11.2 ± 2.3	8.3 ± 1.7	4418 ± 892
East Lansing, MI	2.87 ± 0.21	14 ± 1	102.2 ± 18.4	83.8 ± 15.3	268 ± 17	17.5 ± 0.9	14.7 ± 2.7	7826 ± 1455
Logan, UT	2.36 ± 0.21	14 ± 2	69.4 ± 14.0	62.3 ± 11.8	269 ± 24	15.2 ± 2.2	9.5 ± 2.4	5057 ± 1279
Fort Collins, CO	3.18 ± 0.23	15 ± 1	92.5 ± 11.6	76.2 ± 10.6	192 ± 33	10.5 ± 2.4	7.8 ± 1.5	4152 ± 772
Beltsville, MD	3.66 ± 0.27	15 ± 1	95.2 ± 16.3	82.7 ± 14.4	198 ± 21	16.1 ± 1.6	13.2 ± 2.1	7027 ± 1124
Brawley, CA	3.39 ± 0.34	14 ± 2	85.8 ± 16.6	76.7 ± 14.3	258 ± 37	14.3 ± 3.8	11.0 ± 3.9	5856 ± 2102
Aiea, HI	3.88 ± 0.23	14 ± 2	93.7 ± 19.8	83.4 ± 18.2	316 ± 25	20.7 ± 1.8	17.2 ± 4.0	9157 ± 2106

† To convert liters per hectare (L ha^{-1}) to gallons per acre, divide by 9.35. For 1983 individual sugar, data were not available and thus total sugar is a function of Brix and net stalk yield.
‡ ± denotes SE.

Table 6. Means and range for theoretical ethanol (EtOH) yield and factors directly affecting EtOH production, 1980–1983.

Location	Gross green wt.	Stalk	Net stalk wt.	Total sugars	EtOH
	Mg ha^{-1}	%	Mg ha^{-1}		L ha^{-1}
Fargo, ND	73.0 ± 10.0†	81.8 ± 1.7	60.1 ± 8.0	6.2 ± 1.2	3 300 ± 656
	(42.9 – 104.1)‡	(80.7 – 83.6)	(34.8 – 84.1)	(3.1 – 9.7)	(1 703 – 5 165)
East Lansing, MI	91.8 ± 13.8	69.9 ± 6.4	67.7 ± 13.1	7.8 ± 1.7	4 152 ± 900
	(65.1 – 124.7)	(56.8 – 81.0)	(37.3 – 101.9)	(2.5 – 16.5)	(1 330 – 8 784)
Logan, UT	67.5 ± 13.1	81.8 ± 3.6	56.6 ± 11.4	5.8 ± 1.5	3 087 ± 796
	(42.4 – 92.3)	(76.9 – 88.4)	(33.1 – 80.8)	(3.5 – 11.8)	(1 863 – 6 282)
Fort Collins, CO	91.3 ± 11.6	76.3 ± 3.5	71.0 ± 10.4	6.4 ± 1.4	3 409 ± 746
	(62.8 – 109.0)	(67.2 – 84.6)	(51.4 – 89.5)	(3.2 – 9.8)	(1 703 – 5 217)
Beltsville, MD	75.8 ± 11.2	84.8 ± 2.2	64.9 ± 9.6	7.5 ± 1.3	3 992 ± 710
	(52.4 – 120.1)	(81.2 – 88.8)	(43.5 – 104.5)	(3.8 – 14.3)	(2 023 – 7 613)
Davis, CA	115.2 ± 23.5	78.9 ± 3.2	90.6 ± 19.6	7.6 ± 2.2	4 046 ± 950
	(76.7 – 150.4)	(69.3 – 84.6)	(61.3 – 110.7)	(3.0 – 12.8)	(1 597 – 6 814)
Brawley, CA	81.8 ± 13.6	78.9 ± 4.3	66.7 ± 10.6	7.4 ± 1.8	3 939 ± 961
	(57.8 – 102.4)	(67.6 – 86.1)	(49.1 – 89.2)	(4.5 – 16.6)	(2 395 – 8 837)
Meridan, MS	66.0 ± 11.4	79.0 ± 4.9	52.3 ± 16.0	4.9 ± 0.5	2 608 ± 286
	(53.4 – 96.1)	(64.0 – 80.7)	(38.7 – 75.9)	(4.5 – 5.4)	(2 395 – 2 874)
Aiea, HI	107.8 ± 25.4	78.1 ± 1.0	89.3 ± 21.2	17.2 ± 4.0	9 157 ± 2 206
	(80.9 – 176.1)	(78.1)	(70.8 – 137.6)	(13.7 – 20.9)	(7 293 – 11 127)

† ± denotes SE. ‡ Range.

Table 7. Number of frost-free days and average theoretical EtOH yield 1980-1982.

Days to frost	EtOH	Location
	L ha^{-1}	
120	2182	Fargo, ND
140-143	2827	East Lansing, MI; Logan UT; Fort Collins, CO
180-240	2887	Beltsville, MD; Meridian, MS
280-300	3664	Davis, CA; Brawley, CA
350+	6388	Aiea, HI

bles 2 through 5), but was relatively constant from 1980 through 1982 at such locations as Brawley, CA and Fort Collins, CO. Since EtOH yields for 1983 were computed using brix and net stalk yield and not based on individual sugars, values are considered high. Consequently, 1983 total sugar and EtOH values are considered only for their relative value among locations (Table 5).

When EtOH yield was considered according to the number of frost-free days at each location, an obvious, if not surprising association was found. For the continental U.S. test sites, the number of frost-free days ranged from 120 to 300. This differential was associated with an average 67% increase in EtOH production (from 2182 L ha^{-1} to 3664 L ha^{-1}) (Table 7). Other factors such as fertility, moisture, and planting/harvest dates obviously preclude a strict linear association between number of frost-free days and EtOH yield.

DISCUSSION

Interest in sugar crops as solar energy converters has focused on production of EtOH by fermentation of dilute sugar solutions obtained directly from sugar crops or from the molasses by-product that results from raw sugar production. Technologically, this conversion route is quite appropriate because very little of the energy content of a sugar crop juice is lost when the fermentable sugar is converted into EtOH and carbon dioxide (4). The effect is to convert a virtually noncombustible material into an effective liquid fuel with a high octane rating.

The primary objective of this study was to investigate the yield potential of sweet sorghum grown at diverse geographic locations especially in terms of fermentable sugar production. Lignin and cellulose also were determined because the solar energy conversion process that uses a sugar stalk crop as a collector generates at least as much lignocellulose as simple sugars. Kresovich and Henderlong (7) reporting on the feasibility of sorghum ethanol production, concluded that sorghum can become a promising raw material for ethanol production if all sugar from the culm fibers can be efficiently hydrolyzed and converted to ethanol. Recent lignocellulose research indicates that direct fermentation of lignocellulose to ethanol is possible by use of *Thermocellum* microorganisms (1). More than 700 g kg^{-1} (70%) of the lignocellulose consists of polymers of hexoses and pentoses, with the rest being lignin, waxes, and other materials (9). If the pentoses and hexoses could be converted to ethanol, the value of this sugar stalk crop could be significantly enhanced.

In more tropical areas such as Brazil, sugarcane has proven to be an efficient and dependable source of liquid fuel. Sweet sorghum, like sugarcane and maize, has the C_4 carbon fixation pathway, and thus lacks the process of photorespiration which enables it to achieve maximum short-term crop growth rates (8). Unlike maize, sorghum has the ability to remain dormant during drought periods and then to become active rapidly following moisture reintroduction.

Results of this research suggest that the theoretical EtOH yield of sweet sorghum compares favorably with that of maize. For example, grain maize can be expected to produce about 0.37 L of EtOH pea kg of grain or 2340 L ha^{-1} with a 6.27 Mg ha^{-1} yield. Of course, the storability of grain maize is an attribute which sweet sorghum stalks do not share. The very high yields at the southern tropical location compares favorably with the yield of sugarcane. The advantage of growing sweet sorghum at southern latitudes may be the ease of planting seed as contrasted to the vegetative planting of sugarcane.

Locations selected for this study ranged from 120 to more than 350 frost-free days. It is noteworthy that even at the 120-day location, gross green weight ranged to more than 100 Mg ha^{-1} with as much as 9.7 Mg ha^{-1} of total sugar produced (Table 6). This represents 9.3% fermentable carbohydrates which is comparable to other temperate zone locations which have many more frost-free days. Performance of these essentially random sweet sorghum cultivars at the more northerly latitudes was better than expected considering that they have not been specifically developed for such climate. It was not the purpose of this study to identify favorable locations for growing sweet sorghum, but rather to determine what response could be expected from sites where the crop is not now grown (with the exception of Meridian, MS). Obviously, the study did not include the extreme outer limits of its adaptation. However, it is probable that yield potential would drop off drastically with less than 120 frost-free days. Results of this study demonstrate that sweet sorghum is far more widely adapted than was anticipated for a plant of tropical origin and certainly has the potential for providing a good source of fermentable carbohydrates across a wide geographic area.

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